

## TITANIUM UNDERLAYER FOR LINES IN SEMICONDUCTOR DEVICES

### Field of the Invention

- 5 The present invention relates to the use of a Titanium (Ti) underlayer, together with a Titanium rich Titanium Nitride (Ti rich TiN) layer. More particularly it relates to the use of such layers with metal lines in semiconductor devices

### Background Art

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- Metal lines are used in semiconductor devices to connect components or individual points together. The metal lines are isolated from each other by dielectrics. A typical interconnect line used in semiconductor devices, for instance as is used in CMOS 18 or CMOS 18 shrink, is shown in Figure 1. The line 2 consists of a main, conductive metal layer of aluminium-copper alloy (AlCu layer) 4, with a Ti rich TiN layer 6 above and a Ti rich TiN underlayer 8, below.

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- In an alternative (not shown), both Ti rich TiN layers are replaced with a TiN layer on top of a Ti layer. Such a combination is, for instance shown in published patent document EP-A-0,875,923. According to that document, it is critical that the bottom Ti underlayer has a thickness of from about 90 to about 110 Angstroms ( $10^{-10}$ m). It is exemplified by a metal stack as follows:

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$$x \text{ \AA Ti} / 100 \text{ \AA TiN} / 2300 \text{ \AA Al (0.5\%Cu)} / 50 \text{ \AA Ti} / 400 \text{ \AA TiN}$$

where there were five different thicknesses x between 30 and 200 (Å).

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- A similar combination is shown in published patent document US-B2-6,346,480, where the exemplified stack is:

$$30\text{nm Ti} / 100\text{nm TiN} / 450 \text{ nm Al-Cu} / 15 \text{ nm Ti} / 50 \text{ nm TiN}.$$

- 30 Similar combinations of varying thicknesses are also shown in a number of other published patent documents, for example: US-B1-6,319,727 and US 6,080,657. Other combinations are also known, for instance a TiN or Ti underlayer, beneath a  $\text{TiAl}_3$  layer, beneath a main Aluminium layer beneath another TiN or Ti layer.

- 35 The intervening dielectrics between such known lines are deposited by way of chemical vapour deposition (CVD) techniques. However, the encapsulating dielectrics subject the

metal lines to mechanical tensile stresses, which result in stress induced voids (SIV) in the metal lines. Intrinsically, such dielectrics are compressive films, i.e. the AlCu lines which are encapsulated experience tensile stresses. The stress voids occur as a result of the tensile forces on the grain boundaries. This problem is pronounced when the intermetal dielectric is deposited using high density plasma (HDP) methods, as such materials are known to impart large tensile stresses on the metal lines.

The tensile stresses are also increased when the coefficient of thermal expansion (CTE) between the AlCu interconnect metal lines differ. Thus, when the semiconductor device experiences thermal cycles during its lifetime, the tensile stresses induced on the metal lines are large enough to cause SIVs.

Typically SIVs are wedge shaped voids in the metal lines. Such voids/cracks occur where the yield stress is lowest, which is at the grain boundaries of the metal interconnect lines. In general, the methodology for evaluating such voids is by subjecting the completed semiconductor devices to a period of thermal stress and then checking for SIVs by delayering away the passivating dielectrics and inspecting under a scanning electron microscope (SEM). Typical stress voids are wedge shaped and occur at the grain boundaries where the yield stress is lowest. Figures 2A and 2B show two views of three AlCu metal interconnect lines after the passivating dielectrics are removed. Figure 2A is a top plan view and Figure 2B an isometric view. A stress induced void is clearly present on one of the lines, being approximately 300nm long and 100nm across the width of the line (about one third of the width of the line). However, the voids can be any size and depth, even to the extent of breaking the metal line.

SIVs in AlCu interconnect lines are a reliability concern, as the increase in the resistance of the metal line (as a result of the reduced cross sectional area) will result in device failure, either as a consequence of the increase in the RC time delay constant or because of structural failure if the metal opens. If a fabrication plant is unable to control or avoid such voids, it is unable to obtain suitable qualification for production of relevant devices.

#### Summary of the Invention

It is an aim of the present invention to provide a new metal line. Ideally it would at least partially alleviate the problems with the prior art and reduce the presence of stress voids.

5 According to one aspect of the present invention, there is provided a conductive line for a semiconductor device including: a first conductive layer; a Titanium layer; and a first Titanium rich Titanium Nitride layer between the first conductive layer and the Titanium layer.

10 The invention also provides a silicon substrate having a plurality of such conductive lines thereon.

According to another aspect of the present invention, there is provided a process for manufacturing a conductive line, comprising the steps of: depositing a Titanium layer onto a substrate; depositing a first Titanium rich Titanium Nitride layer to the other side of said Titanium layer relative to said substrate; and depositing a first conductive layer to the other side of said first Titanium rich Titanium Nitride layer relative to said Titanium layer.

20 In general terms, the invention is the provision of a Titanium underlayer beneath a Titanium rich Titanium Nitride layer in a metal line on a silicon substrate to reduce stress voiding. The Titanium underlayer is preferably thin.

25 The Titanium layer is preferably a 75Å layer, providing an actual thickness of about 60 to 110Å.

The invention also provides semiconductor devices, memories and integrated circuits including one or more such conductive lines.

#### Brief Summary of the Drawings

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The invention will now be further described, by way of non-limitative example with reference to the accompanying drawings, in which:-

Figure 1 is a schematic view of a cross-section of a prior art metal line;

35 Figures 2A & 2B are enlarged views of a prior art set of metal lines, with various layers stripped away, showing the presence of a stress induced void;

Figures 3A & 3B show different test structures used to test the metal lines produced; Figure 4 is a schematic view of a cross-section of a metal line of the present invention; Figure 5 shows the results of X-Ray diffraction analysis of various metals; and Figure 6 is a TEM picture through an embodiment of the present invention.

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#### Specific Description

In the following description and elsewhere the thicknesses of various layers are given. In relation to the present invention, except when otherwise indicated, these are nominal  
10 thicknesses, based on deposition time and deposited rate. These may differ from actual thicknesses due to difficulties in obtaining accurate deposits. This is typical in the wafer fabrication business.

The following description relates mainly to a process for producing interconnect lines for  
15 CMOS18 structures. A typical 18 $\mu$ m (micron) technology integrated circuit has six metal layers, with silicon-rich-oxide liners and intermetal dielectrics (IMDs) between the layers. Each metal layer typically consists of an AlCu layer sandwiched between Ti or TiN layers. The relative thicknesses for the components of each layer can vary through the stack. With layer M1 being the lowermost layer and layer M6 being the uppermost, the  
20 thicknesses of the layers of a typical current metal stack may be constituted as follows:

M1-M4: 250A Ti rich TiN / 4000A AlCu / 250A Ti-rich TiN

M5-M6: 500A Ti rich TiN / 8000A AlCu / 250A Ti-rich TiN

With the intention of overcoming the SIV problem, the inventors tried various  
25 experiments, including: varying the use of N<sub>2</sub>O during CVD or annealing, varying the etching machine, varying aspects of post etch cleaning, breaking the vacuum between TiN and AlCu deposition, modifying the metal strip recipe, modifying the high density plasma recipe, using sub-atmospheric (SA) CVD for the intermetal dielectric between layers M5 and M6 (IMD5) and providing a thicker silicon-rich-oxide liner on the metal line  
30 between the metal line and the IMD. None of these worked. For example SA CVD is known to impart, intrinsically, compressive stresses on the metal lines, which would prevent metal stress voids. However, SACVD is intrinsically in tension at all times, which makes it susceptible to cracking

35 The inventors then tried other approaches, in particular experiments based on variation in the Metal 1 level in CMOS 18 to examine metal stack changes and metal deposition

temperatures on SIV. It was thought that by modifying the underlying barrier metal or by changing the deposition temperatures, it could help to change the grain structure of the metal lines and/or act as a stress relief layer, so as to reduce the tensile stress on the metal lines. The details of the different combinations of materials, their thicknesses and deposition temperatures are shown in Table 1.

Expt No.	Stack Composition - All figures in Å ( $10^{-10}\text{m}$ )	Deposit Temp ( $^{\circ}\text{C}$ )
1a	75stdTi / 4000AlCu / 250TixTN	270
1b		450
2a	150stdTi / 4000AlCu / 250TixTN	270
2b		450
3a	250TixTN / Flash Ti100 / 4000AlCu / 250TixTN	270
3b		450
4a	300stdTi / 250TixTN / 4000AlCu / 250TixTN	270
4b		450
5a	250TixTN / 4000AlCu / 250TixTN	300
5b		350
5c		400
5d		450
6a	150ALPS Ti / 100TiN / 4000AlCu / 250TixTN	270
6b	250ALPS Ti / 100TiN / 4000AlCu / 250TixTN	270
6c	250ALPS Ti / 100TiN / 4000AlCu / 250TixTN	270
6d	300ALPS Ti / 100TiN / 4000AlCu / 250TixTN	270
6e	300ALPS Ti / 100TiN / 4000AlCu / 250TixTN	450
7	160IMP Ti / 70CVD TiN / 4000AlCu / 250TixTN	270
8	160IMP Ti / 4000AlCu / 250TixTN	270

Table 1

10 where

“std”: pure Ti that is deposited by standard Physical Vapour deposition (PVD) methods.

“Flash”: another name referring to pure Ti.

“ALPS”: Advanced Low Pressure Sputtering

“IMP”: Ionised Metal Plasma

“TixTN”: Ti-rich Ti- Nitride - The TixTN is deposited by first sputter-depositing Ti for a few seconds and then flowing N<sub>2</sub> gas into the chamber to form a TiN layer.

For each experimental stack two different types of structures were created, on the same wafer, for different tests. The structures are shown in Figures 3A and 3B.

Figure 3A shows an NIST (National Institute of Standards and Technology - US) test structure. It is a small electromigration Extrusion-type structure, having 3 lines and being 800  $\mu\text{m}$  (microns) long, with a pattern density (PD) of about 48%.

Figure 3B shows a second, yield module (YM) test structure, with a large, comb meander-type structure, with metal layers M1 to M4 having a top surface area of 6.66mm<sup>2</sup> and metal layers M5 to M6 having a top surface area of 20mm<sup>2</sup>, with a PD of about 50%. This is a typical type of metal structure that can be expected in an integrated circuit.

To be acceptable the results from a production process must pass a post stress SIV visual inspection on a sample from each layer. The inspection requires that the wafer be stressed, for instance by keeping at 200°C for 24 hours. The passivation layer and the IMD layers are removed through delayering and reactive ion etching (RIE) to expose all the metal lines. This is followed by a visual inspection of design rule structures in a SEM. For both NIST and the second (YM) tests, the necessary criteria for passing are shown in Table 2.

Stress void size (as % of width of metal line)	Criteria
10-25%	< 30voids/cm
25-50%	< 10voids/cm
>50%	0 voids/cm

Table 2

The results of the two tests on the various experimental stacks are shown in Table 3.

Expt No.	YM			NIST		
	10-25%	25-50%	>50%	10-25%	25-50%	>50%
1a	375	0	0	525	112.5	0

2a	4375	875	0	462.5	125	0
2b	10000	1500	0	1875	575	0
3a	17500	15000	0	2000	1262.5	0
3b	4250	875	0	1137.5	925	50
4a	0	0	0	35	0	0
4b	0	0	0	62.5	12.5	0
5a	0	0	0	37.5	12.5	0
5b	0	0	0	500	200	0
5c	0	0	0	225	0	0
5d	0	0	0	12.5	0	0
6a	625	1250	0	125	450	37.5
6b	875	375	0	12.5	0	0
6c	1000	500	0	0	0	0
6d	1500	625	0	225	500	125
6e	1125	500	0	125	112.5	0
7	250	0	0	150	0	0
8	2500	125	0	2250	450	0

Table 3

5 The actual counts were conducted over 80  $\mu\text{m}$  (microns) and the results multiplied up by 12.5.

10 Thus experimental stack No. 5a passes all the criteria for the YM test structure, but fails one of them for the NIST structure. In particular, there are 37.5 voids/cm along the metal line whose size is between 10-25% of the width of the metal line. This is greater than the 30 voids/cm allowed. There are also 12.5 voids/cm whose size is between 25-50% of the width of the metal line. This is greater than the 10 voids/cm allowed.

15 Stack 1b was not tested as stack 1a did not work and it was deemed pointless to consider stack 1b.

From the results, it can be seen that experiment No. 4a (300A Ti underlayer beneath the current metal stack) shows some of the most promising results. From this table other layers would also appear to be promising, but were not useful for other reasons. For instance, stack 5d was not considered because it was not compatible with the IMD

being, which was a fluorinated silicate glass (FSG). At a high temperature of 450°C, the fluorine would outgas and (among other things) cause corrosion to the metal lines.

- Further experiments were then necessary to determine the optimal thickness of the Ti underlayer. New stacks were produced, with a Ti underlayer deposit at different temperatures and different thicknesses beneath a 250Ti/TN / 4000Al / 250Ti/TN stack, as shown in Table 4.

Expt No.	Deposit Temp. °C		Ti Underlayer Thickness Angstroms ( $10^{-10}\text{m}$ )					
	100	150	0	75	150	200	300	450
11	X			X				
12	X				X			
13	X					X		
14	X						X	
15	X							X
16		X				X		
17		X					X	
18		X						X

Table 4

The maximum nominal thickness is a 450Å Ti underlayer. Typically this might lead to a physical thickness of up to 500Å. The thinnest layer tried was 75Å (nominal). Thinner layers may be possible but become increasingly difficult to achieve.

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The visual SIV results for these experiments are shown in Table 5

Expt No.	Yield %	YM			NIST		
		0-25%	25-50%	>50%	0-25%	25-50%	>50%
11	82.5	0	0	0	0	0	0
12	75.9	0	0	0	12.5	0	0
13	74.7	0	125	0	25	0	0
14	69.3	0	0	0	0	0	0
15	65.7	0	0	0	25	0	0
16	71.7	0	0	0	0	0	0
17	63.3	0	0	0	0	0	0

18	68.1	0	0	0	62.5	0	0
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Table 5

Completed wafers were tested electrically. The yield indicated in Table 5 is the number of passing integrated circuits (ICs) compared to the total number of ICs, given as a percentage.

Thus the clearest results are from experiments 1, 4, 6 and 7. However, of these the highest yield was achieved in experiment no. 11. This experiment shows that a 75Å Ti underlayer deposited at 150°C is sufficient to improve the SIV substantially. It is generally desired for the Ti thickness to be as thin as possible to reduce deposition time and to reduce the impact for the metal etch process. Lower production temperatures are also preferred, mainly for fear of the fluorine outgassing from the FSG. It is also desirable to reduce the thermal budget for the transistors, which may show some drift in characteristics when the thermal budget changes.

An interconnect line of the present invention to be used in semiconductor devices, for instance in CMOS 18 or CMOS 18 shrink, is therefore shown in Figure 4. This is at least nominally similar in cross-section to the line of Figure 1, differing in the addition of the Ti underlayer 22, and the result it has on the other layers. The line 20 thus consists of a main, conductive metal layer of aluminium-copper alloy (AlCu layer) 24, with a Ti rich TiN layer 26 above and a Ti rich TiN underlayer 28, below, and a Ti layer 22 lowermost.

Further experiments were conducted to qualify the extra 75Å Ti underlayer. Metal lines were deposited on a number of wafers, in NIST test structures, using different amounts of DC power. One lot was deposited at 1500W and another at 2000W. The difference that this makes is in the deposition rate. The higher the DC power, the faster the deposition rate. From a process point of view, 1500W Ti is preferred over 2000W Ti due to better thickness control. The lower power requirement allows better process tuning and control of thickness. The construction of lines on each wafer involved metal layer deposit, followed by standard photolithography and standard etching for each of layers M1 -M6. Table 6 shows the structure of each layer

M1-M4 Deposit	75Å Ti	250Å Ti <sub>x</sub> TN	4000Å AlCu	250Å Ti <sub>x</sub> TN	SiON deposit
M5-M6 Deposit	75Å Ti	500Å Ti <sub>x</sub> TN	8000Å AlCu	250Å Ti <sub>x</sub> TN	SiON deposit

Table 6

- 5 The SIV visual inspection results for a 1500W Ti recipe wafer is shown in Table 7. This was post stressing at 200°C for 24 hours.

Stress void size (as % of width of metal line)	Total No. of Voids in Metal Layers/cm						Maximum Allowed
	M1	M2	M3	M4	M5	M6	
10%-25%	4	0	4	0	0	0	30/cm
25%-50%	4	0	0	0	0	0	10/cm
>50%	0	0	0	0	0	0	0/cm

Table 7

- 10 The SIV visual inspection results for a 2000W Ti recipe wafer is shown in Table 8. This was post stressing at 200°C for 24 hours.

Stress void size (as % of width of metal line)	Total No. of Voids in Metal Layers/cm						Maximum Allowed
	M1	M2	M3	M4	M5	M6	
10%-25%	0	13	0	0	0	0	30/cm
25%-50%	0	4	0	0	0	0	10/cm
>50%	0	0	0	0	0	0	0/cm

Table 8

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In this case, the M2 layer is the worst due to experimental variation.

As can be seen by comparing the results with the maxima in the last column in each of Tables 7 and 8, all SIV visual criteria are met for both Ti underlayer recipes.

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A yield study was conducted with several of the wafers. There was no statistical difference in the yield between the two recipes for Ti underlayer deposit.

- 25 Metal sheet resistances were also compared against baseline lots. Comparison of the sheet resistances with baseline lots for three months showed that the addition of the 75Å

Ti underlayer did not affect the sheet resistance of the metal lines for thin and thick metal lines.

In order to know the effects of the extra 75Å Ti underlayer on metal etch on metal bridging and continuity, separate window checks were done. The main conclusion from the window experiments is that the current metal etch for CMOS18 and CMOS18 Shrink would be able to cope with the extra 75Å Ti without any amendments to the etch recipe. The metal continuity and bridging of the metal lines would not be affected by the extra 75Å Ti.

The main conclusions from these experiments are as follows:

- i. SIV are reduced with the inclusion of an addition 75Å Ti underlayer
- ii. SIV visual inspection results are equivalent for SP and ST recipes
- iii. Yield results are statistically equivalent for both split legs
- iv. Metal sheet resistances are unaffected by the inclusion of the extra 75Å Ti underlayer
- v. The current metal etch would be able to cope with the extra 75Å Ti with no deterioration in metal continuity and bridging.

X-RAY Diffraction (XRD) analysis was performed to seek to determine the crystal orientation with the addition of the 75Å Ti underlayer and the results are shown in Figure 5. Compared with standard thin metal (i.e. the conventional layer with 4000Å AlCu), thin metal with the Ti-underlayer becomes almost fully (220) orientated, and the (111) and (311) orientations become suppressed. Compared with standard thick metal (i.e. the conventional layer with 8000Å AlCu), thick metal with the Ti-underlayer has more grains with (311) and (111) orientation.

To understand the physical thickness of the 75Å Ti underlayer, a Transmission Electron Microscope (TEM) was used to provide a picture of the cross-section of a (thick) metal M5 layer, with the result shown in Figure 6 for the lower part of the metal layer. The physical thickness of the 75Å Ti underlayer is about 100Å. This apparent difference is because the described thicknesses are actually calculated based on deposition time and deposited rate and may therefore vary from what is actually deposited. This is typical in the wafer fabrication business. Thus the physical thickness of a 75Å layer may, in fact be between around 60 to 110Å.

One hypothesis for the reason the invention works is that the improvement is a result of a change in the grain orientation of the metal lines (in particular the main metal, exemplified by AlCu), thereby increasing the resistance of the metal lines to stress migration and/or void nucleation resulting in better resistance to SIV. Another hypothesis is that the Ti underlayer has a coefficient of thermal expansion (CTE) in between the intermetal dielectric and the AlCu lines, which results in the Ti underlayer acting as a stress buffer layer.

Although the invention has been exemplified with layers of various specific thicknesses, the invention is not limited to these. Although most test were conducted with a 75Å Ti underlayer, other thicknesses for the Ti underlayer would also work (as is shown in the results in Table 5 above). Other thicknesses of Ti/TN also work (as is shown in the results in Tables 7 and 8 above). Other thicknesses of some of the other layers would also be expected to work.

Whilst the present invention has been exemplified by a AlCu metal line, it also covers lines of other metals and alloys, in particular other Aluminium alloys (for example with magnesium, silicon, a lanthanide or palladium).

Thus the present invention provides an improved product and process based on the addition of an extra Ti layer below a Ti rich TiN layer in a conductive line.